Recent experimental results on Longitudinal multiplicity and flow fluctuations in heavy-ion collisions

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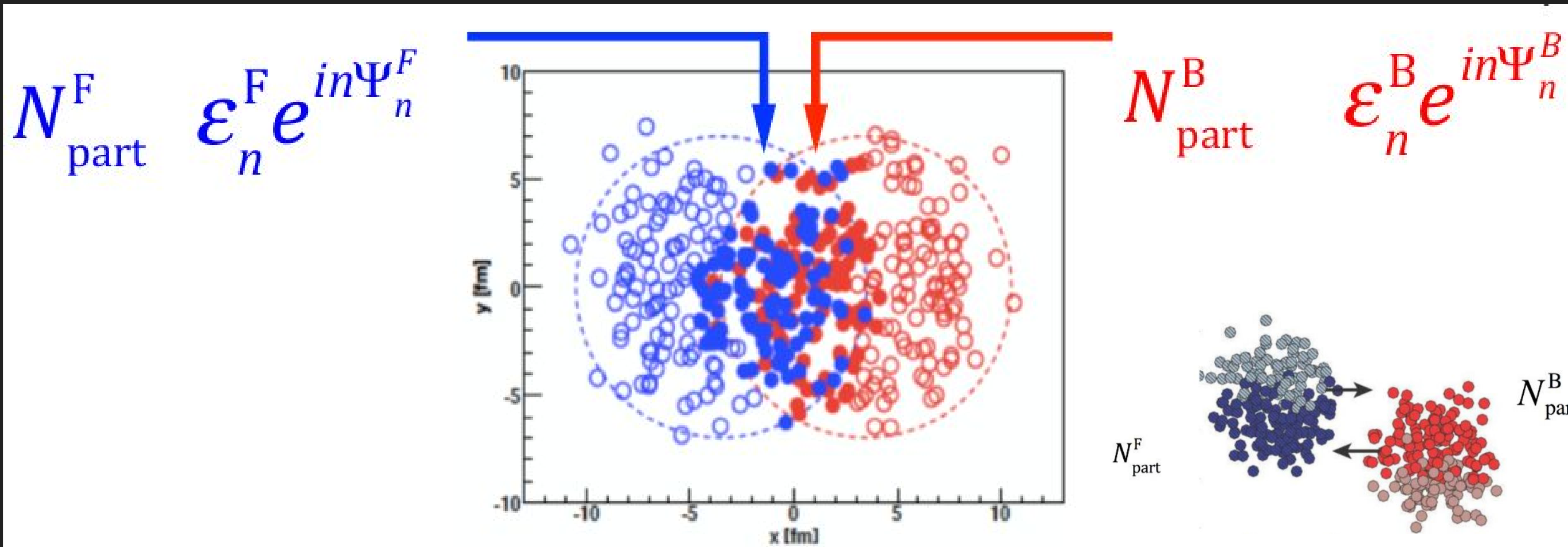
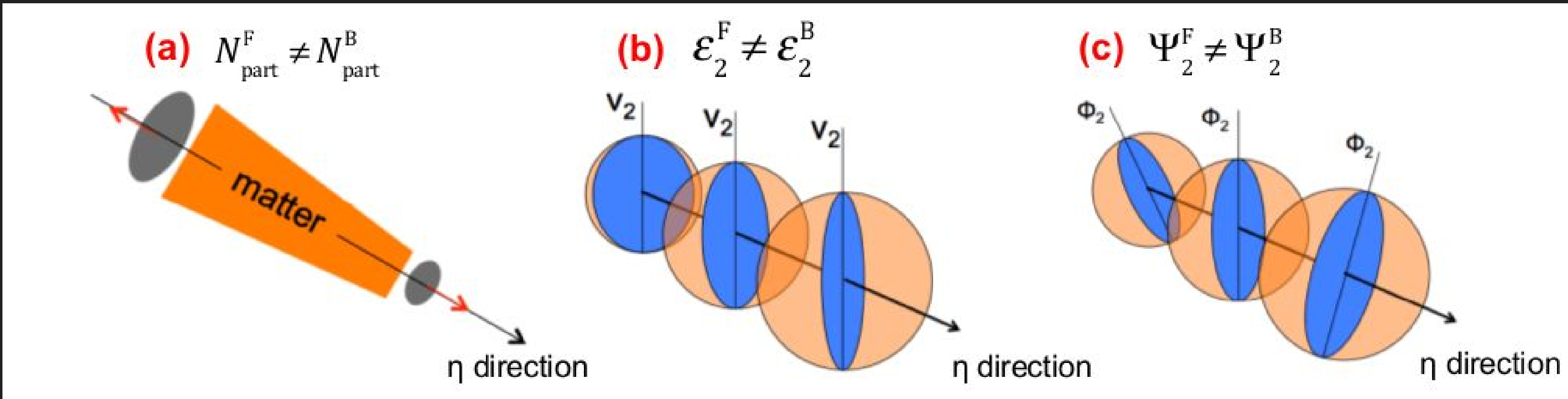
RHIC & AGS User's Meeting-2016

Origin of longitudinal fluctuations



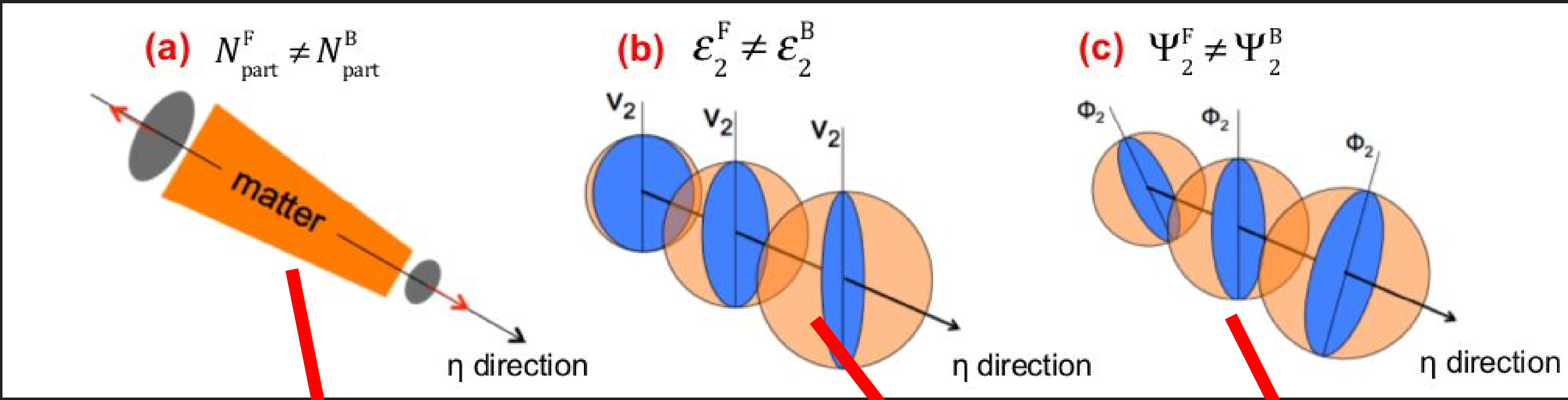
- Can see it in simple MC Galuber model picture
- Forward & backward going participant distributions are not symmetric

Consequence of longitudinal fluctuations



- Forward & backward going participant distributions are not symmetric
- Three effects of asymmetry:
  - N^{F}_{part} != N^{B}_{part}
  - ε^{F}_{n} != ε^{B}_{n}
  - Ψ^{F}_{n} != Ψ^{B}_{n}

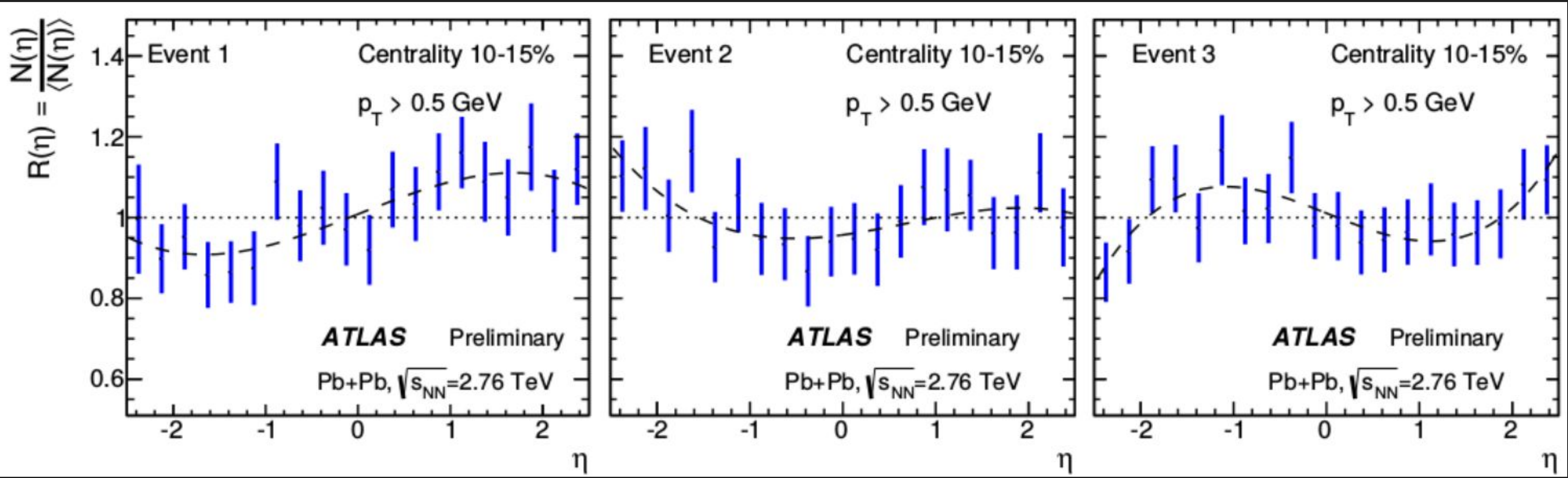
Observing longitudinal fluctuations



Event-by-Event Multiplicity Fluctuations along η. (ATLAS)

EbE Flow fluctuations, in magnitude and direction along η. (CMS)

EbE Forward-backward (FB) Multiplicity fluctuations



Event-by-Event single-particle multiplicity distributions (normalized): $R_S(\eta) \equiv \frac{N(\eta)}{\langle N(\eta) \rangle}$

ATLAS-CONF-2015-020

- Observe clear multiplicity fluctuations along η.
- However single-particle observable cannot be easily used to study correlated fluctuations.

Multiplicity correlation functions

Measure FB fluctuations using two-particle correlations

$$C(\eta_1, \eta_2) = \frac{\langle N(\eta_1) N(\eta_2) \rangle}{\langle N(\eta_1) \rangle \langle N(\eta_2) \rangle} \equiv \langle R_\mathrm{S}(\eta_1) R_\mathrm{S}(\eta_2) \rangle \ , \quad R_\mathrm{S}(\eta) \equiv \frac{N(\eta)}{\langle N(\eta) \rangle}$$

ATLAS-CONF-2015-020
ATLAS-CONF-2015-051

Multiplicity correlation functions

Measure FB fluctuations using two-particle correlations

$$C(\eta_1,\eta_2) = \frac{\langle N(\eta_1)N(\eta_2)\rangle}{\langle N(\eta_1)\rangle\langle N(\eta_2)\rangle} \equiv \langle R_{\mathrm{S}}(\eta_1)R_{\mathrm{S}}(\eta_2)\rangle \ , \quad R_{\mathrm{S}}(\eta) \equiv \frac{N(\eta)}{\langle N(\eta)\rangle}$$

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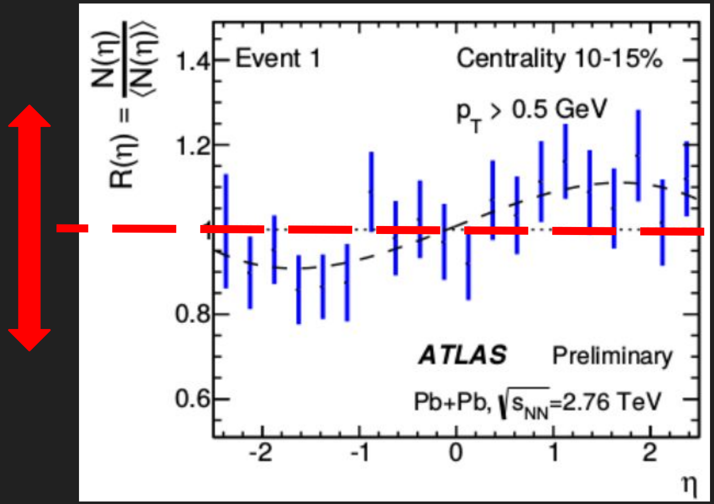
ATLAS-CONF-2015-051

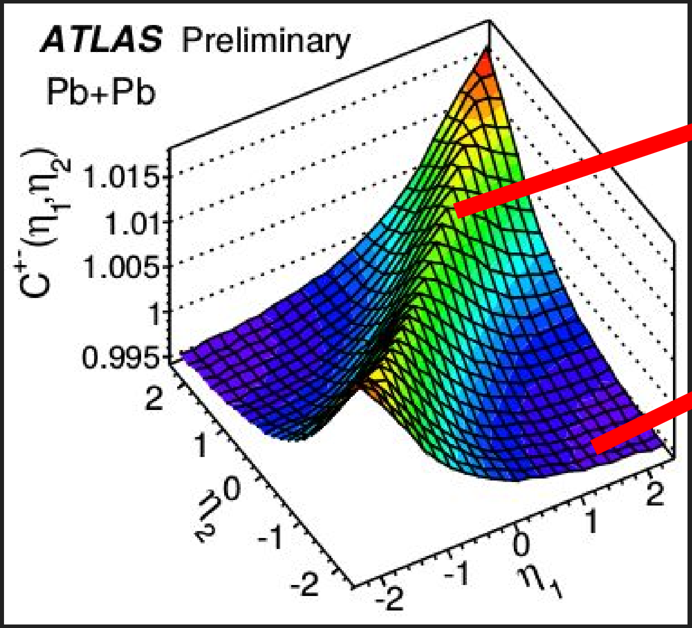
Renormalize to remove overall multiplicity fluctuations (single particle modes)

$$C_{\mathrm{N}}(\eta_1,\eta_2) = \frac{C(\eta_1,\eta_2)}{C_p(\eta_1)C_p(\eta_2)} \ ,$$

$$C_p(\eta_1) = \frac{\int_{-Y}^{Y} C(\eta_1,\eta_2)\,d\eta_2}{2Y}, \quad C_p(\eta_2) = \frac{\int_{-Y}^{Y} C(\eta_1,\eta_2)\,d\eta_1}{2Y}$$



Short-range correlations



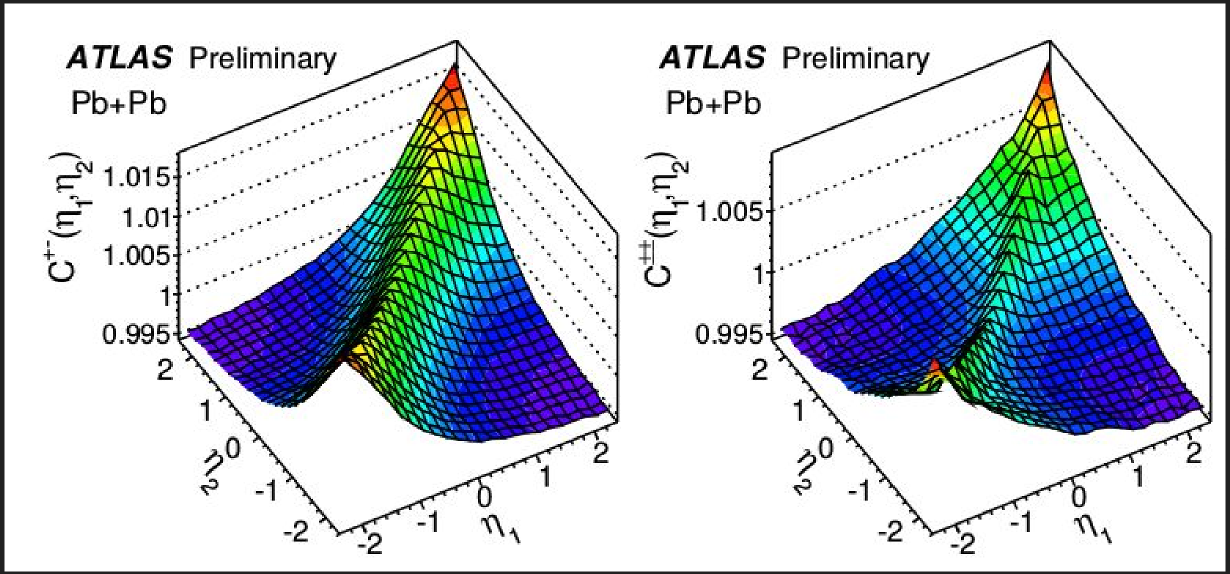
Short-range correlations (Jets, decays) produce ridge-like structure along $\eta_1=\eta_2$.

This must be removed first, before extracting features of the genuine long-range correlation that sits underneath

Short-range correlations

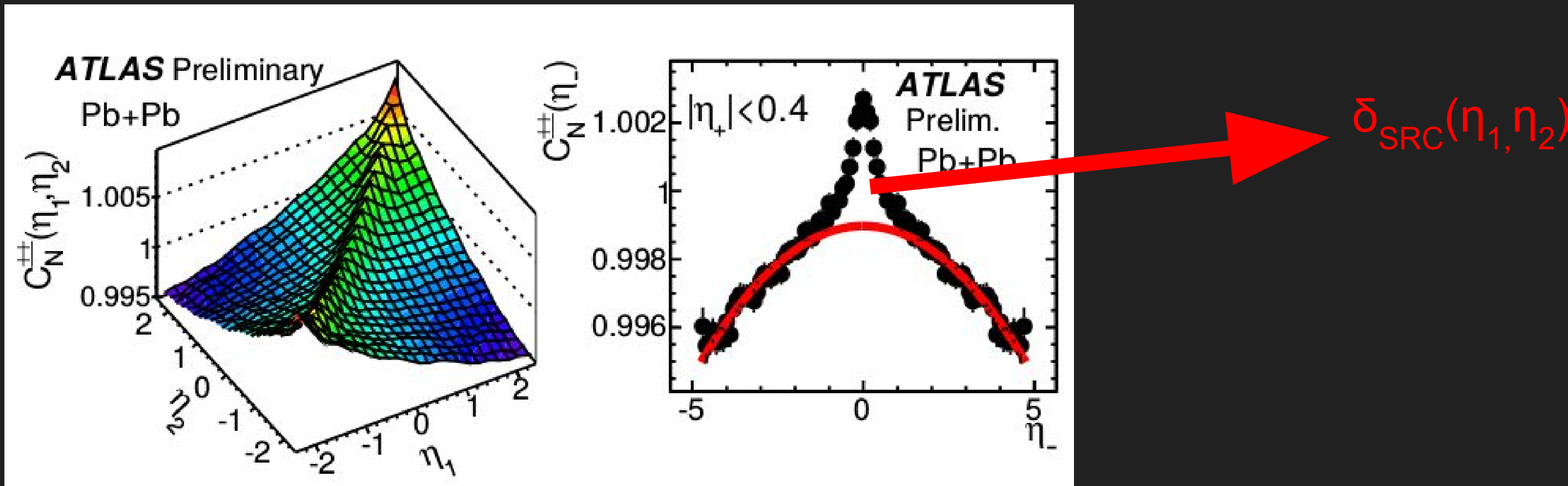
Opp-Charge pairs

Same-Charge pairs

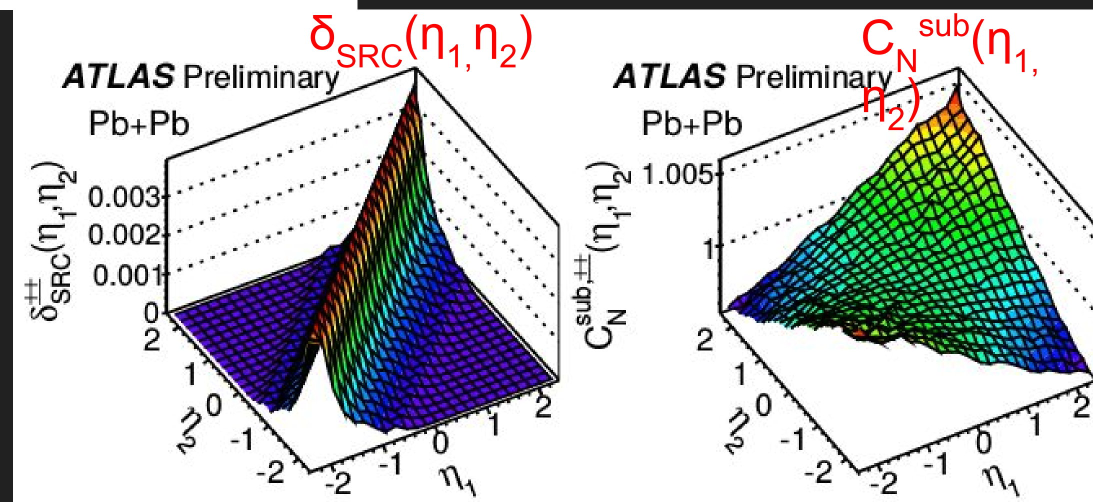


- Short-range correlations depend strongly on relative sign of particle pairs.
- Much larger for opposite-sign (left) than like sign pairs (right).
- Long range correlation quite identical!

Short-range correlations : Removal

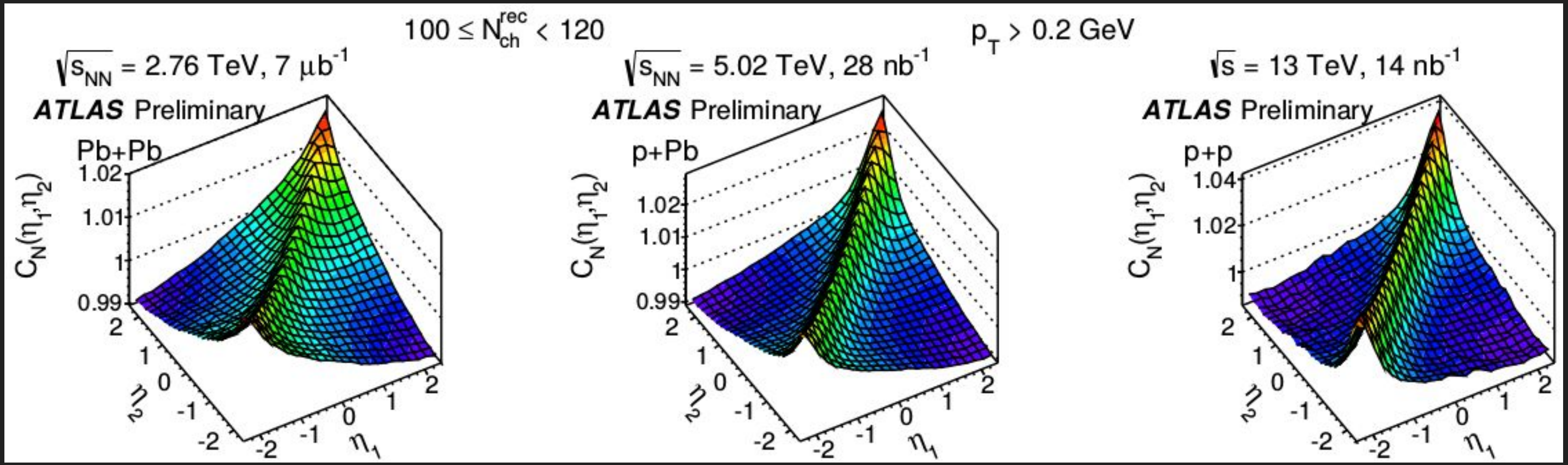


- SRC is estimated by fitting 1D projection along η_1-η_2 with quadratic function over the range $|\eta_1$-$\eta_2|>1.5$
- Excess over fit is assumed to be SRC and is removed
- Remaining correlation is the genuine long-range correlation: $C^{sub}(\eta_{1,}\eta_2)$



Extension to pp and p+Pb

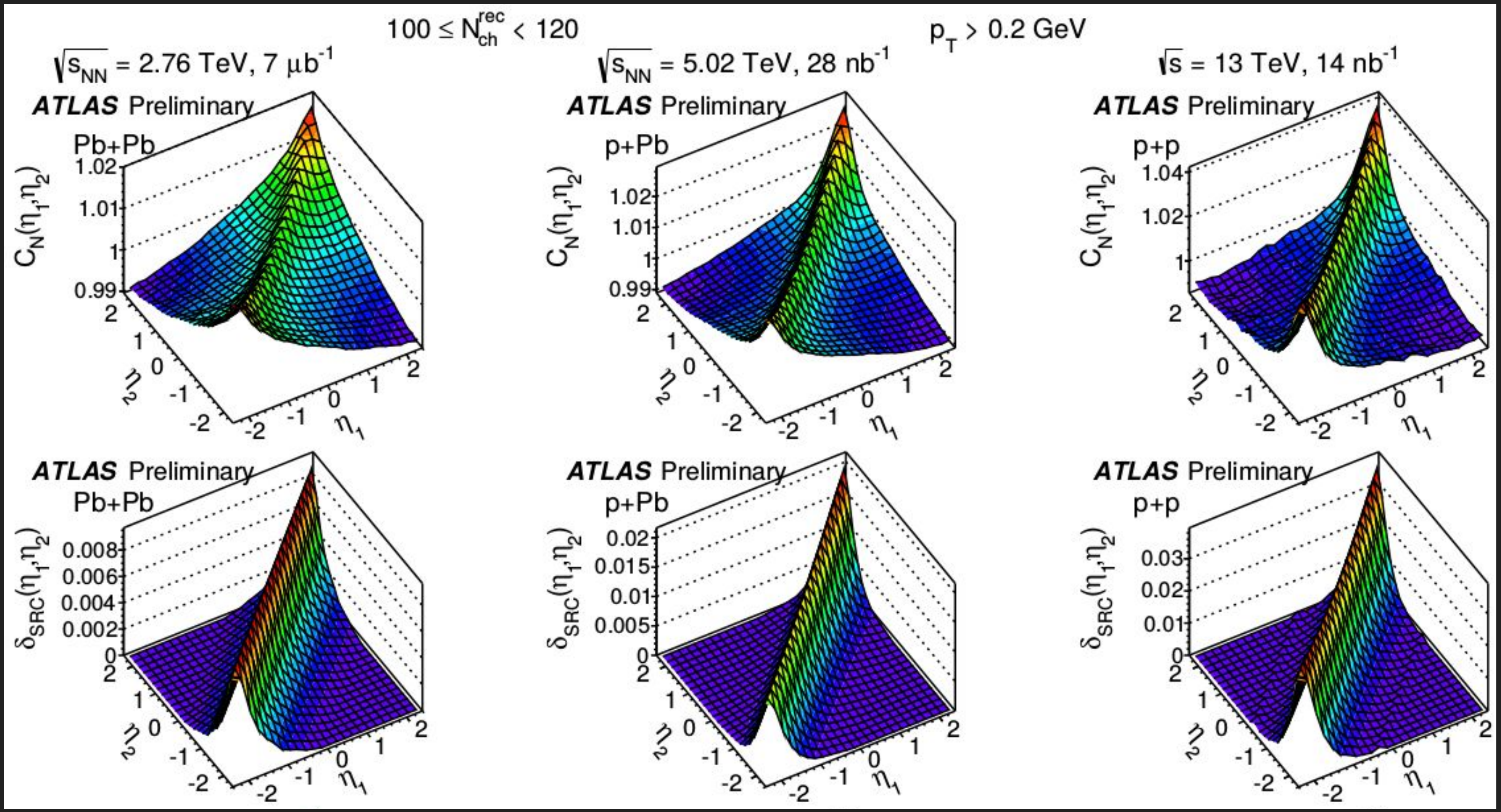
$C_N(\eta_1, \eta_2)$



Extension to pp and p+Pb

$C_N(\eta_1, \eta_2)$

$\delta_{SRC}(\eta_1, \eta_2)$

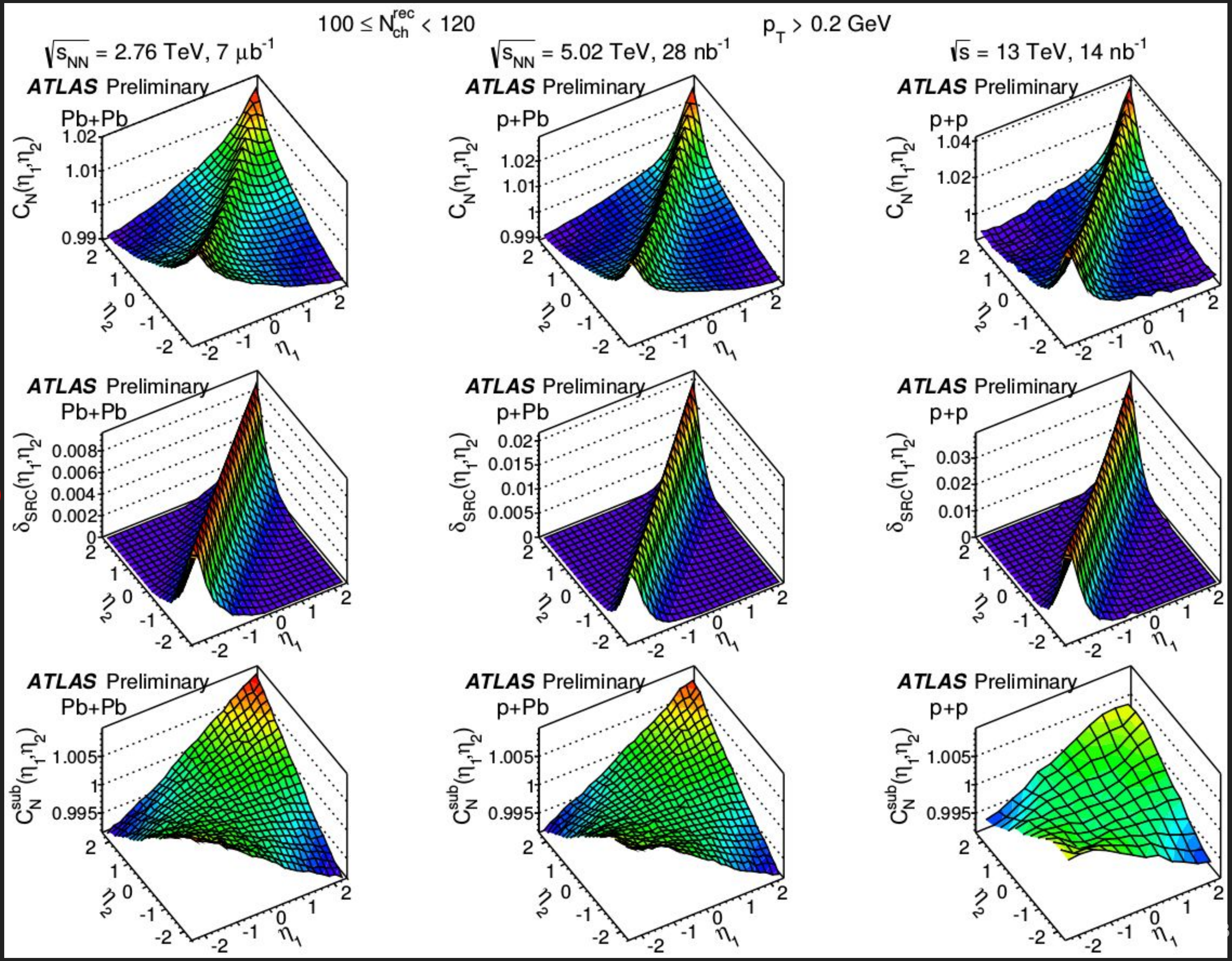


Extension to pp and p+Pb

$C_N(\eta_1, \eta_2)$

$\delta_{SRC}(\eta_1, \eta_2)$

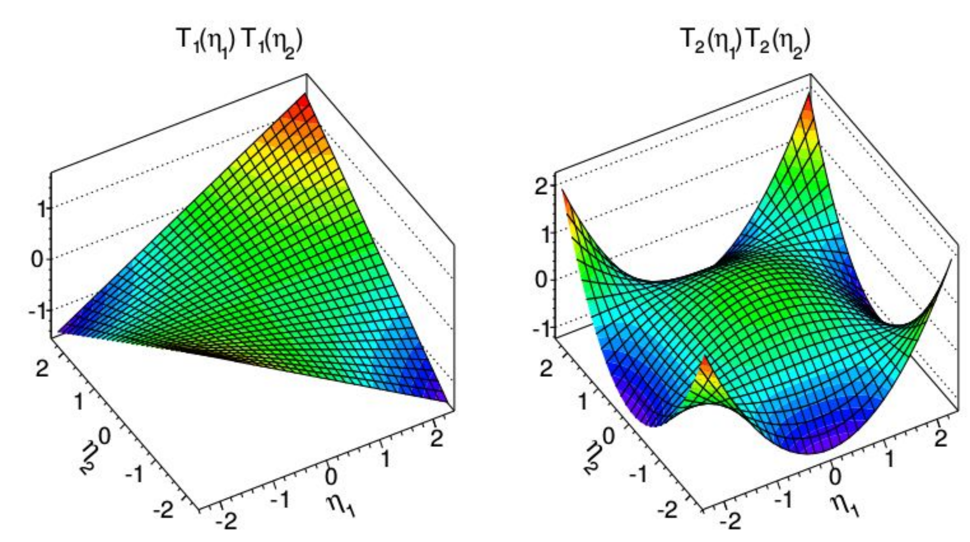
$C_N^{sub}(\eta_1, \eta_2)$



Quantifying the LRC

The LRC is quantified by expanding the correlation function in a 2D Legendre-function basis (arXiv:1210.1965: A. Bzdak, D.Teaney):

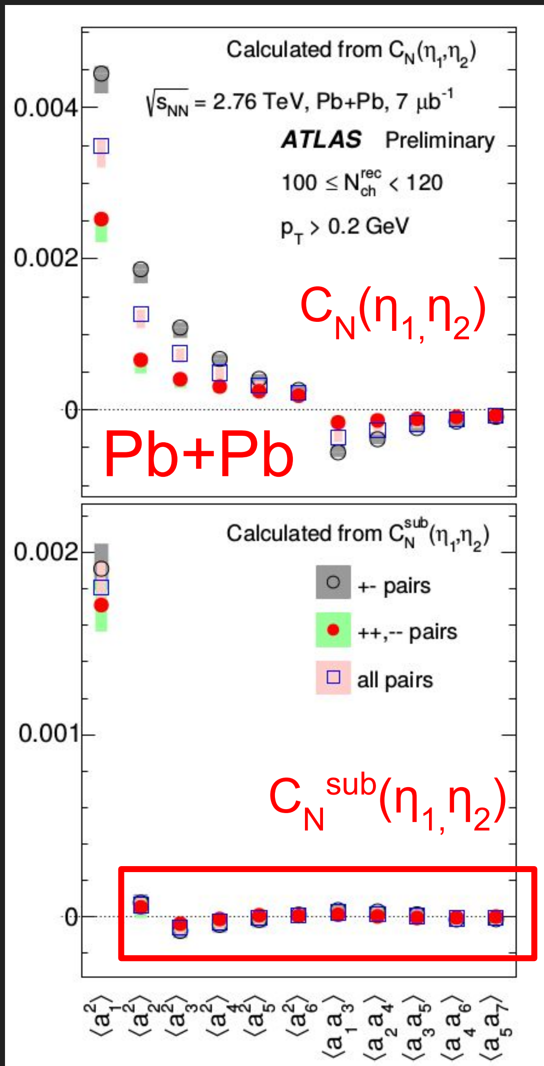
$$C_N(\eta_1,\eta_2) = 1 + \sum_{n,m=1}^{\infty} a_{n,m} \frac{T_n(\eta_1)T_m(\eta_2) + T_n(\eta_2)T_m(\eta_1)}{2}, \quad T_n(\eta) \equiv \sqrt{\frac{2n+1}{3}} Y\, P_n\left(\frac{\eta}{Y}\right)$$



Example basis functions T_1T_1 and T_2T_2

Coefficients of the expansion $a_{m,n}$ quantify the correlation strength

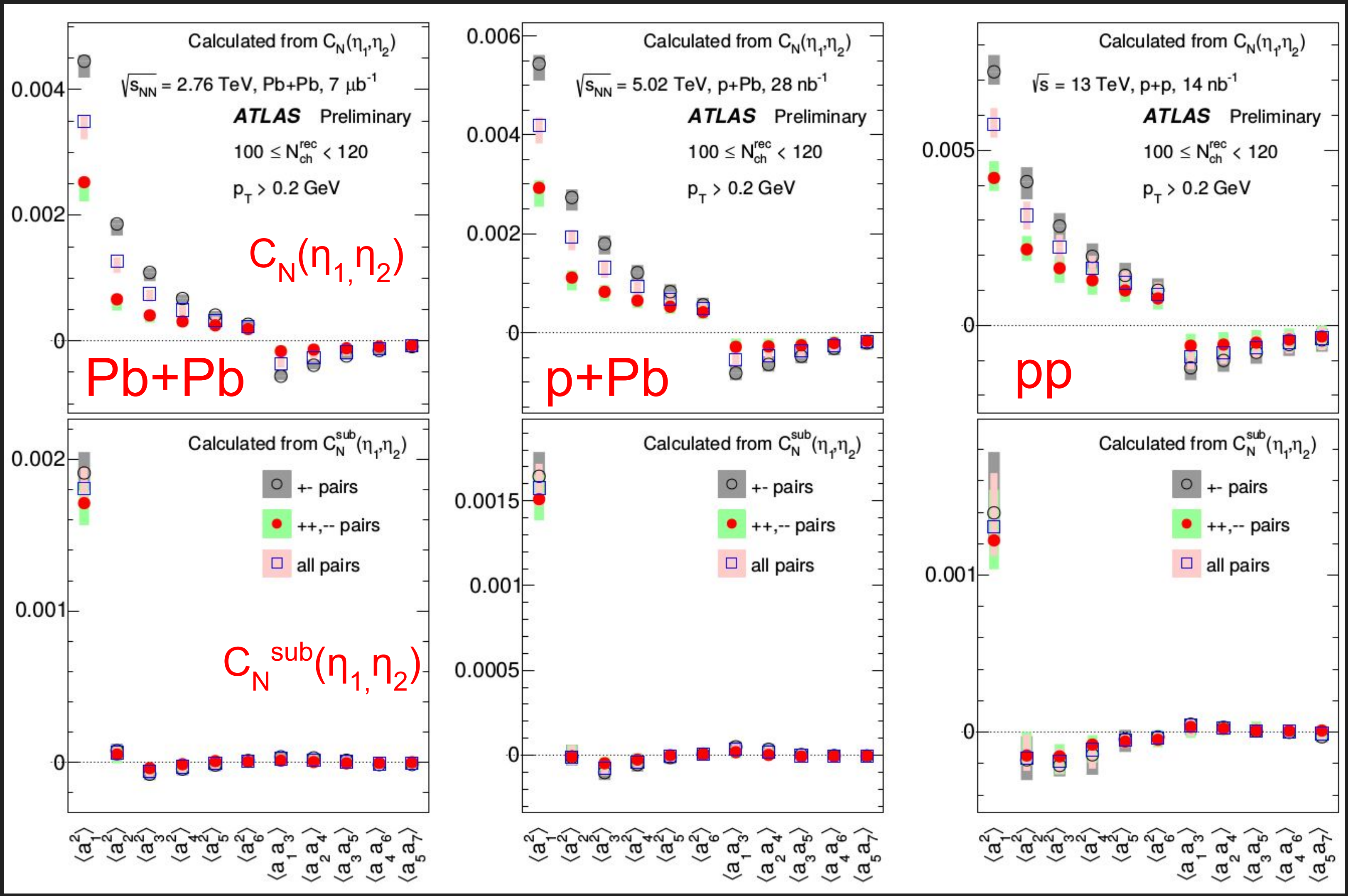
Correlation coefficients $a_{m,n}$



- Before SRC removal, several non-zero $a_{m,n}$ are observed.
- Significant difference between same-charge and opposite charge pairs

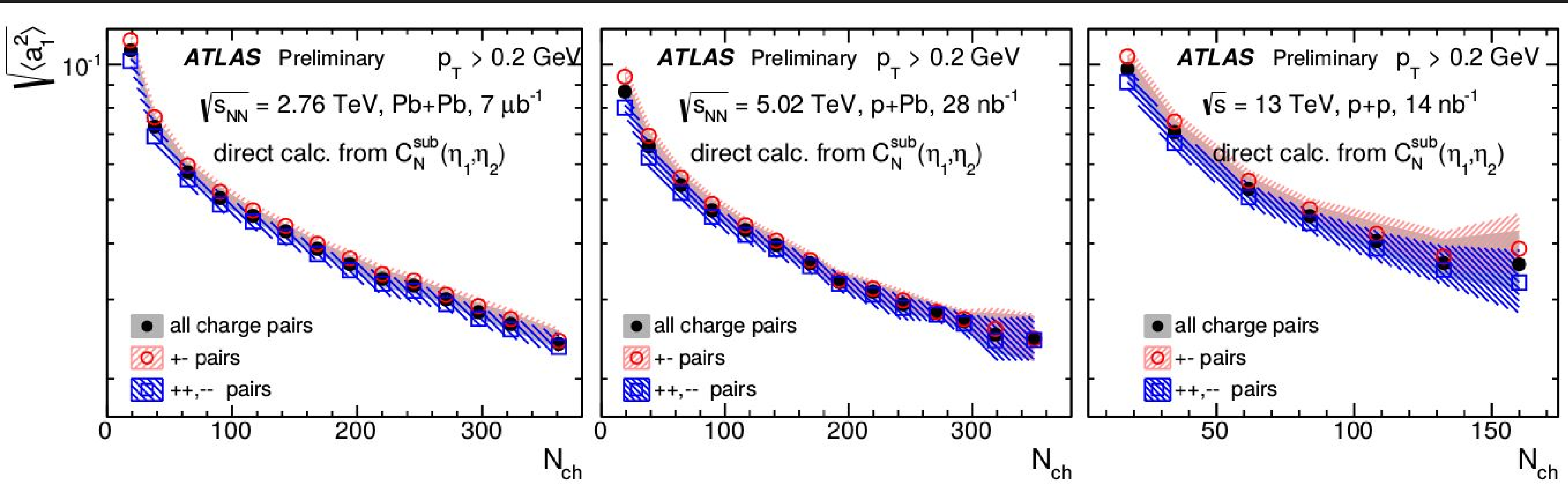
- After SRC removal, only $a_{1,1}$ is significant.
- FB fluctuation dominated by linear single-particle component
- Consistency between same-charge and opposite charge pairs

$a_{m,n}$: Dependence on colliding system



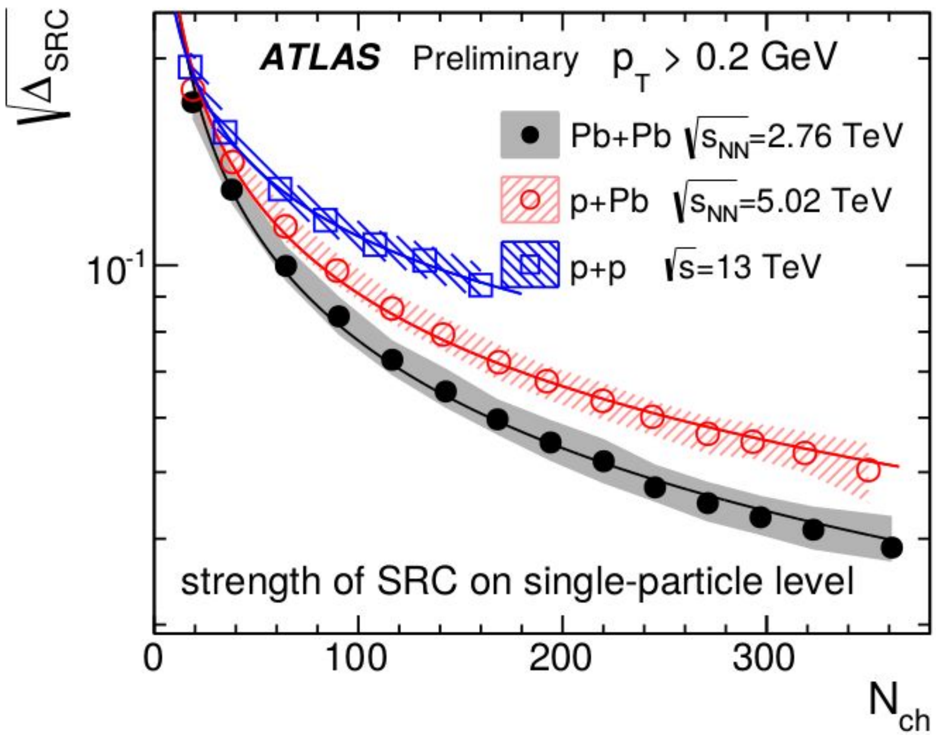
Same observation for pp and p+Pb

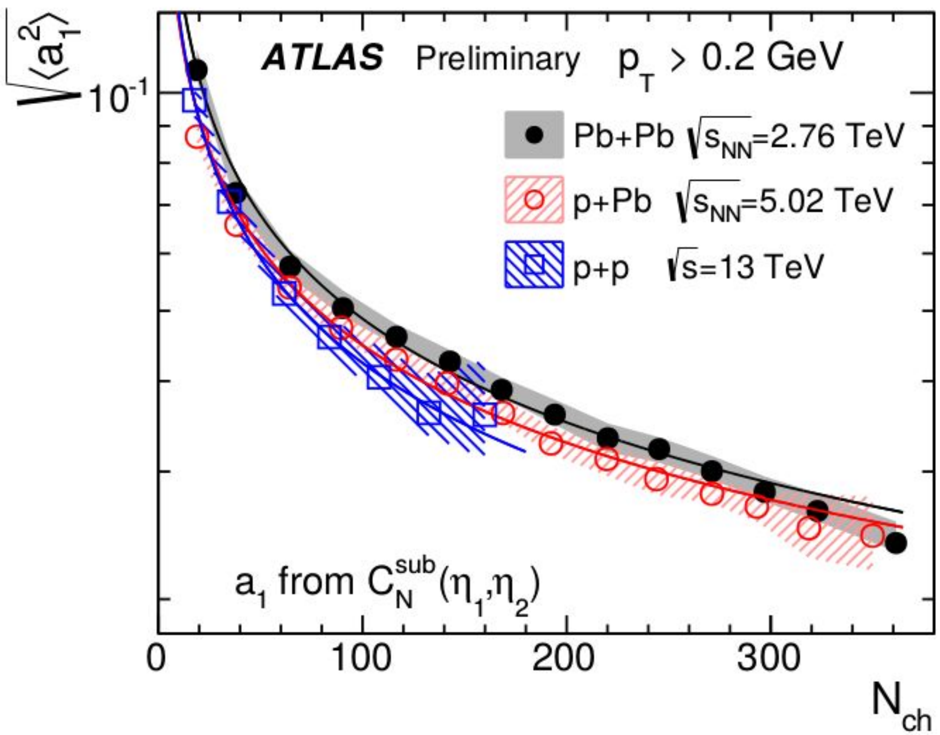
Multiplicity dependence of a_1:



- Decreases with increasing N_{ch}.
- Identical for different charge combinations across all multiplicities.
- Quite similar between pp, p+Pb and Pb+Pb (Note: different x-axis range)

SRC vs LRC

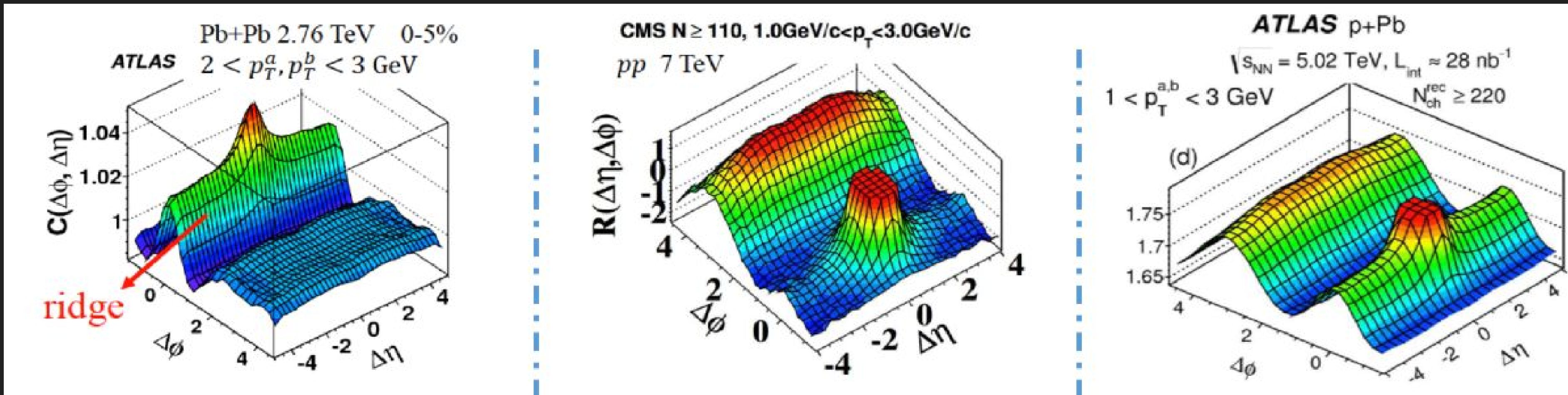


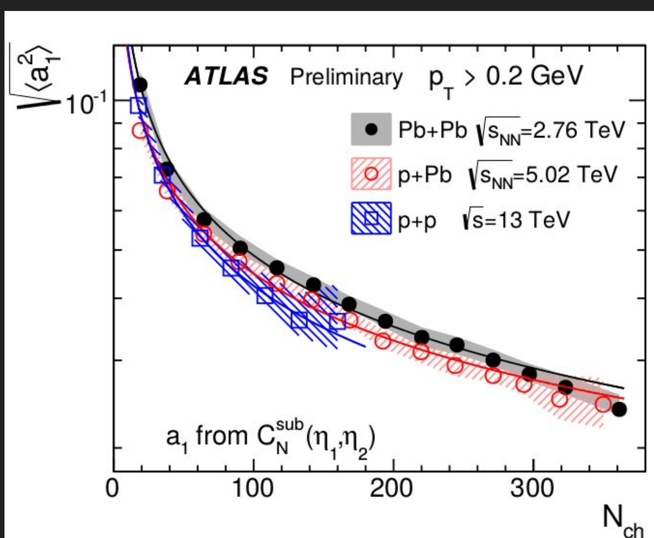


- SRC is quite different for the three systems
  - Largest for pp smallest for A+A (at same multiplicity)

- Quite comparable LRC for pp, pA and AA!

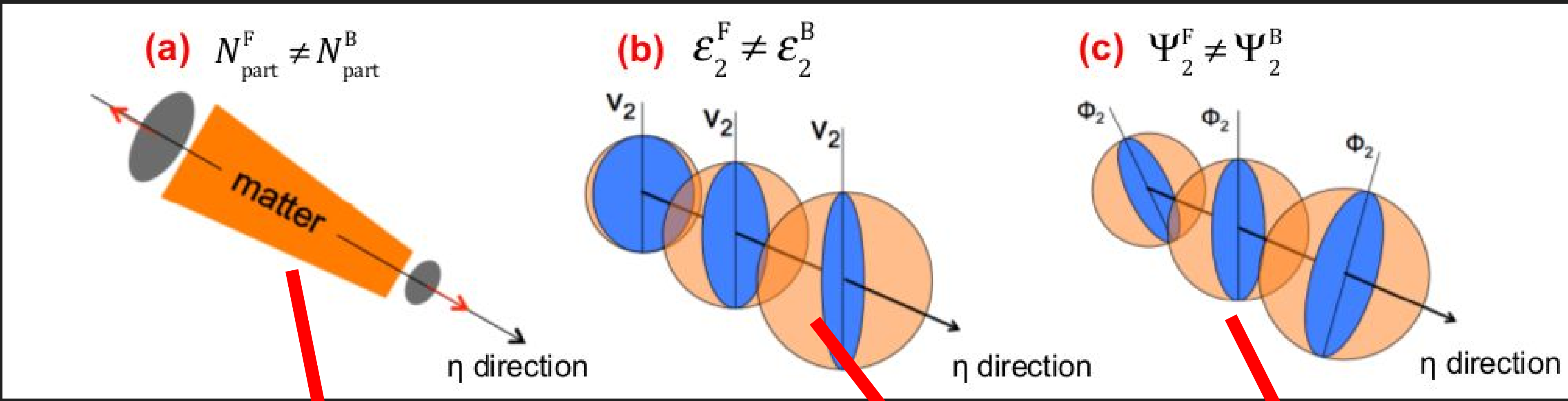
Similarity of LRC for pp, p+Pb and Pb+Pb





pp, pA and AA are similar on multiple fronts!

Longitudinal flow fluctuations

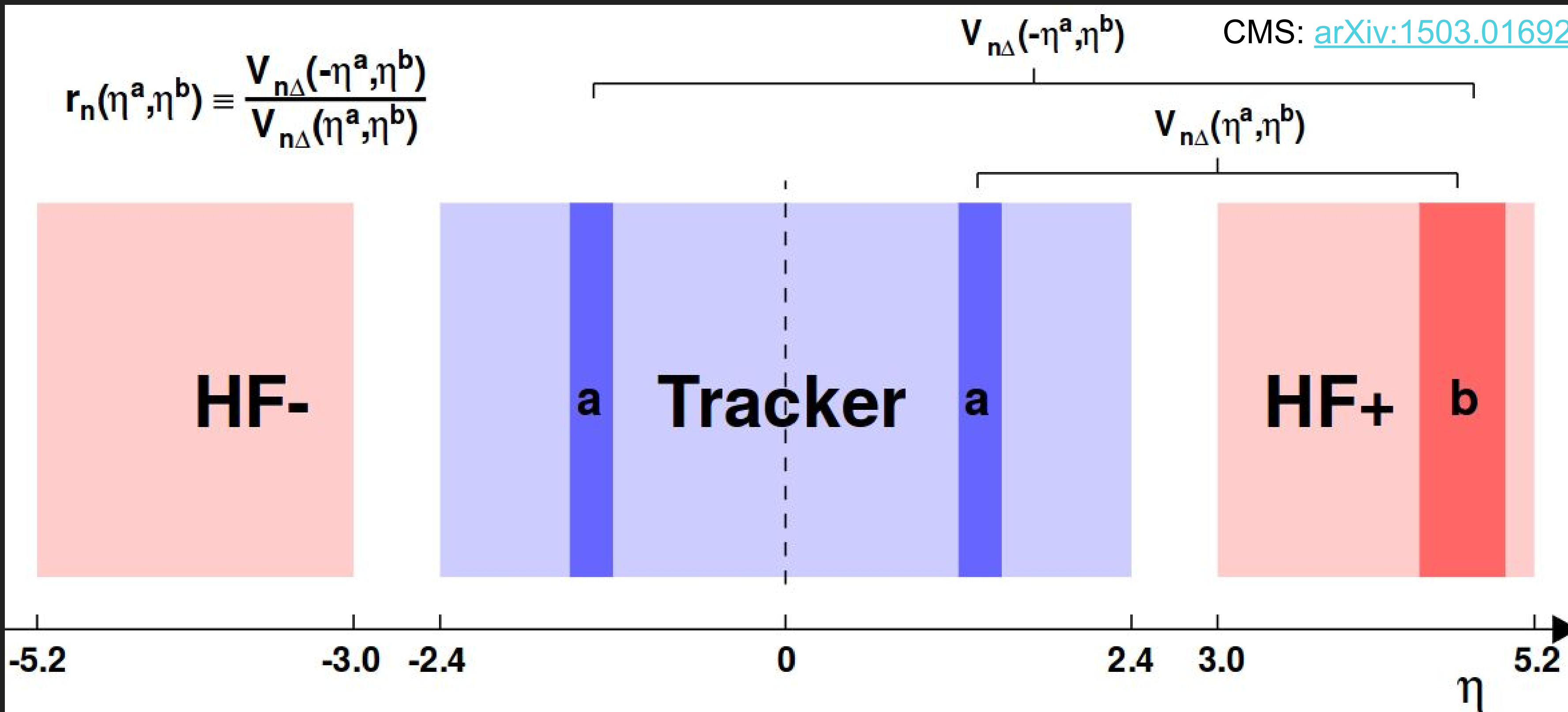


Event-by-Event Multiplicity Fluctuations along η. (ATLAS)

EbE Flow fluctuations, in magnitude and direction along η. (CMS)

Quantifying the Event-plane rotation

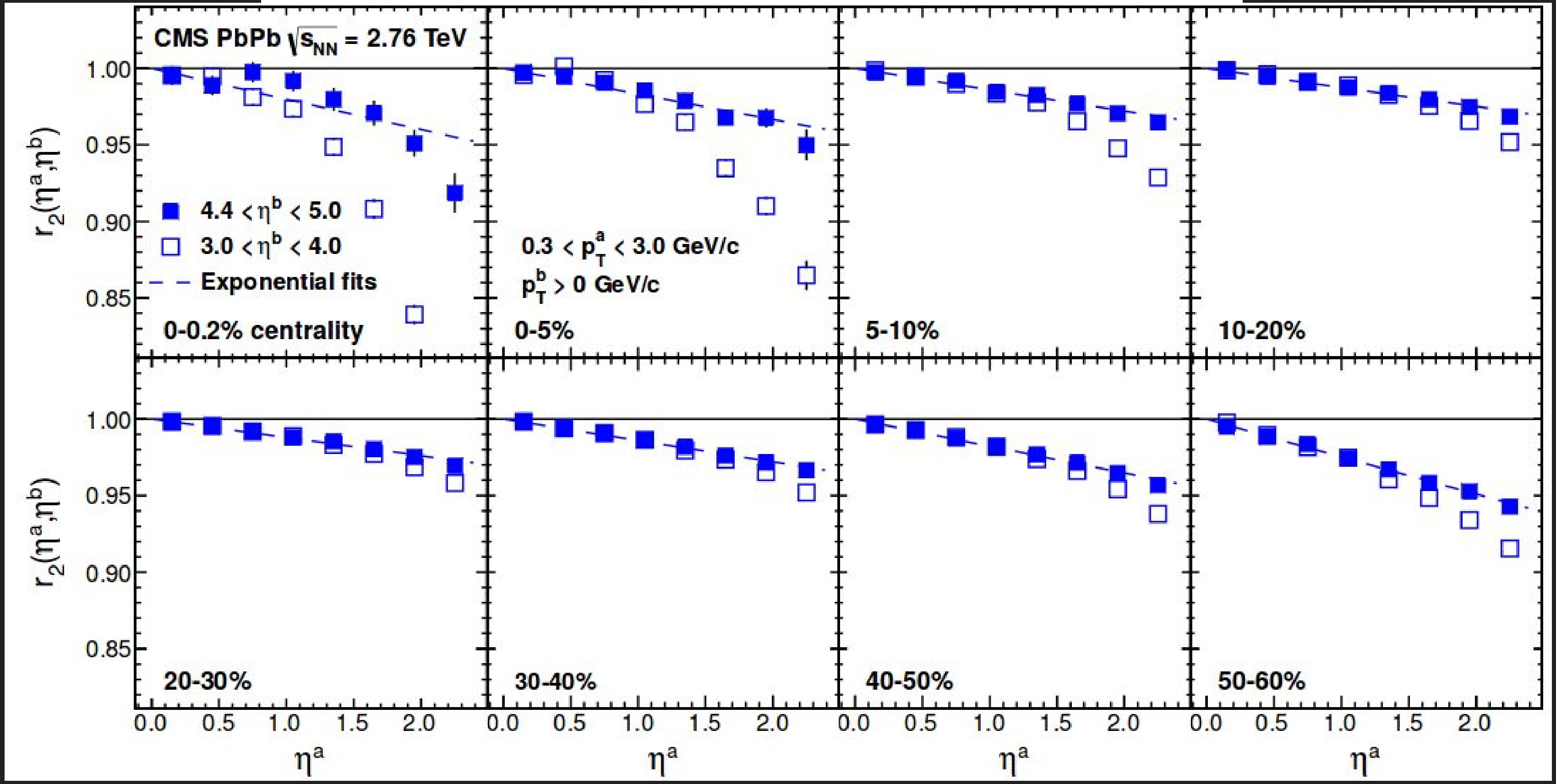
$$v_{n\Delta}(\eta^a,\eta^b)=\langle v_n(\eta^a)v_n(\eta^b)\rangle \longrightarrow v_{n\Delta}(\eta^a,\eta^b)=\langle v_n(\eta^a)v_n(\eta^b)\cos(n\Psi_n(\eta^a)-n\Psi_n(\eta^a))\rangle$$



$$r_n(\eta^a,\eta^b)=\frac{\langle v_n(-\eta^a)v_n(\eta^b)\cos[n(\Psi_n(-\eta^a)-\Psi_n(\eta^b))]\rangle}{\langle v_n(\eta^a)v_n(\eta^b)\cos[n(\Psi_n(\eta^a)-\Psi_n(\eta^b))]\rangle}\sim\langle\cos[n(\Psi_n(\eta^a)-\Psi_n(-\eta^a))]\rangle$$

Event-plane rotation: Ψ_2

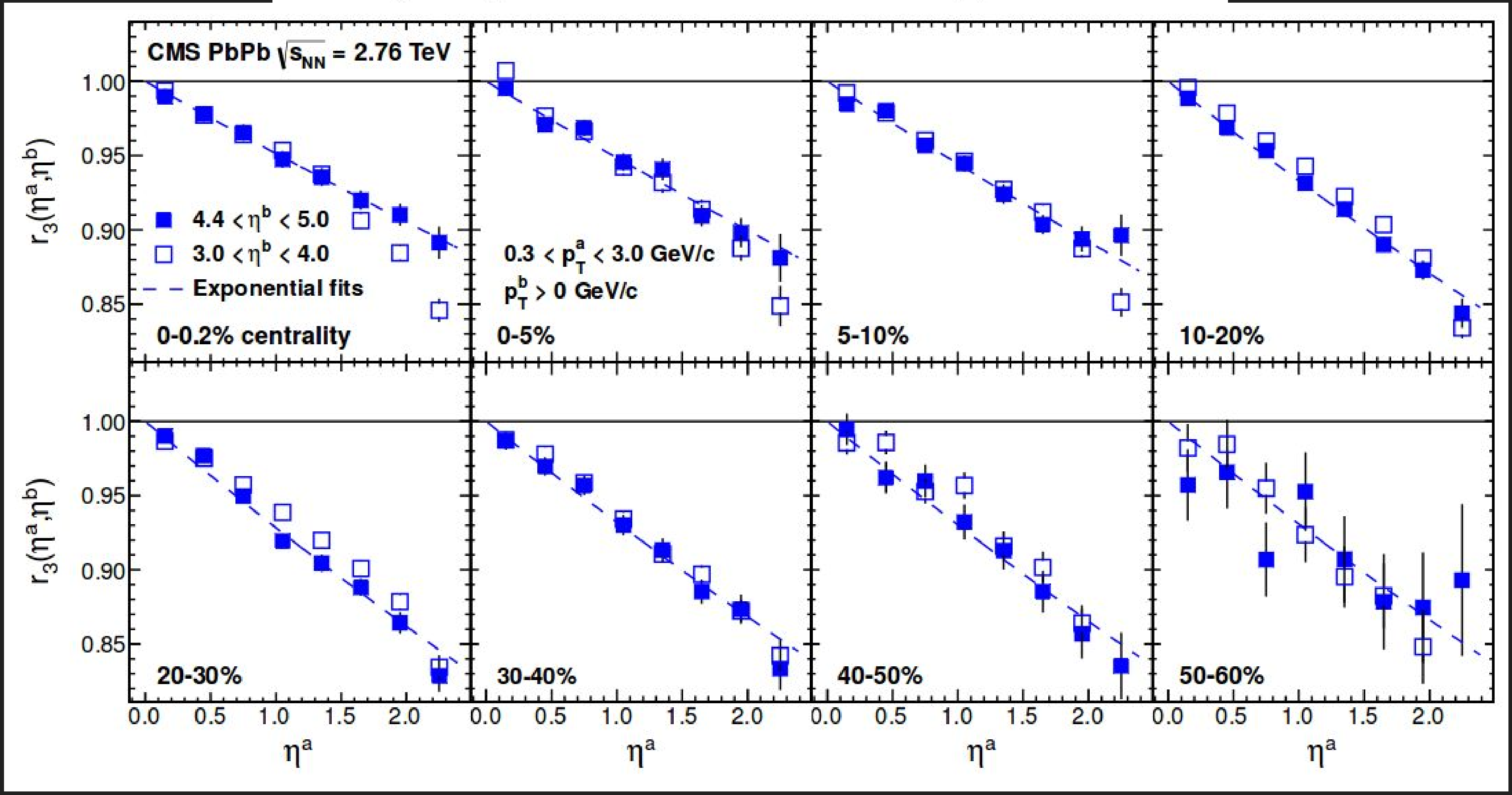
$$r_n \approx \left\langle \cos\left(n\Psi_n(\eta^a) - n\Psi_n(-\eta^a)\right)\right\rangle \approx e^{-2F_n^\eta \eta^a}$$



- Clear de-correlation (rotation) observed
- Observable has some dependence on choice of reference bin
  - Dependence is smaller in mid-central events and for $\eta^a<1$
- Effect decreases from central->mid-central then increases again

Event-plane rotation: Ψ_3

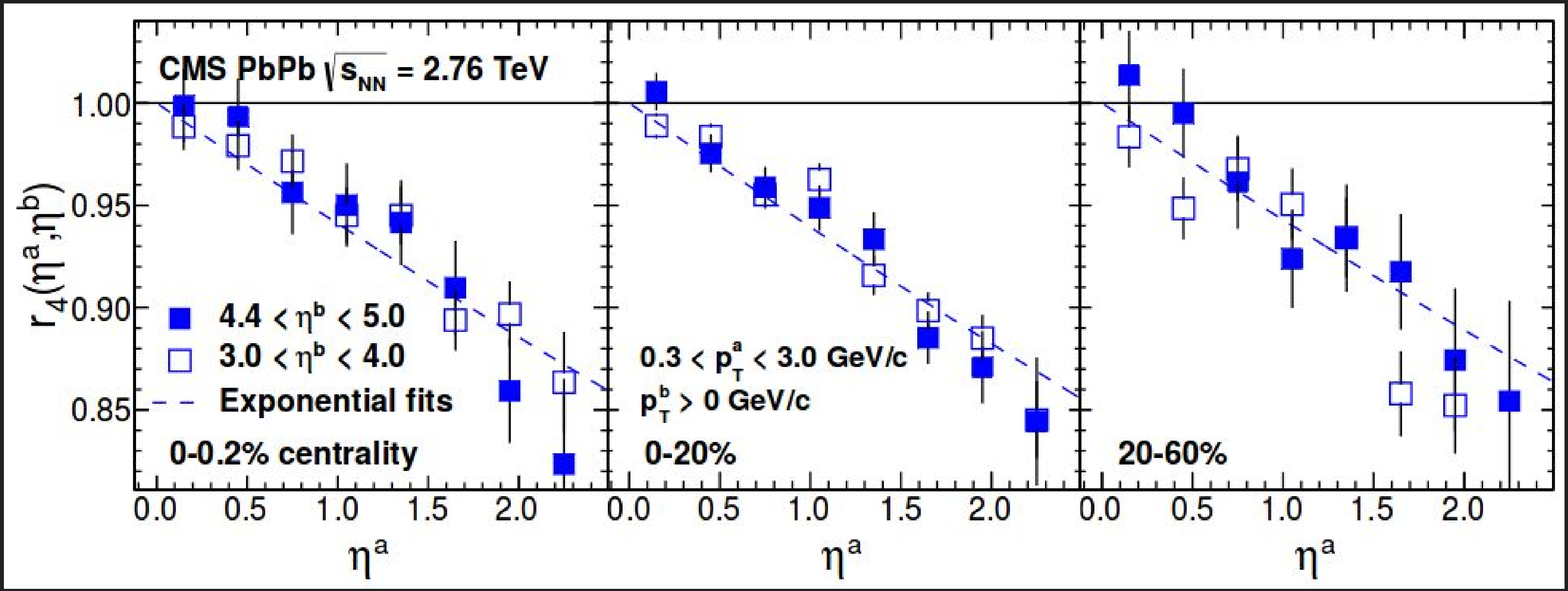
$$r_n \approx \left\langle \cos\left(n\Psi_n(\eta^a) - n\Psi_n(-\eta^a)\right)\right\rangle \approx e^{-2F_n^{\eta}\eta^a}$$



- Significantly larger rotation for n=3
- Nearly independent of choice of reference bin
- Not much centrality dependence

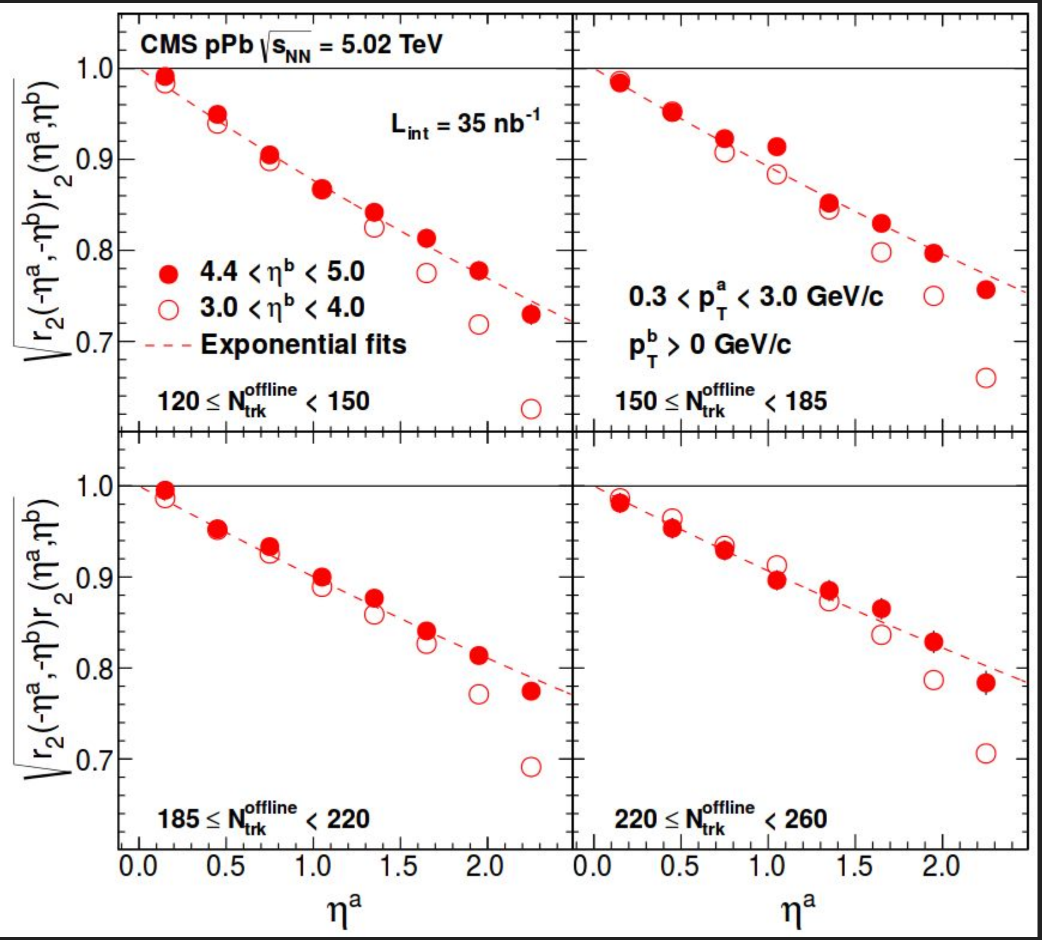
Event-plane rotation:Ψ_4

$$r_n \approx \left\langle \cos\left(n\Psi_n(\eta^a) - n\Psi_n(-\eta^a)\right)\right\rangle \approx e^{-2F_n^\eta \eta^a}$$



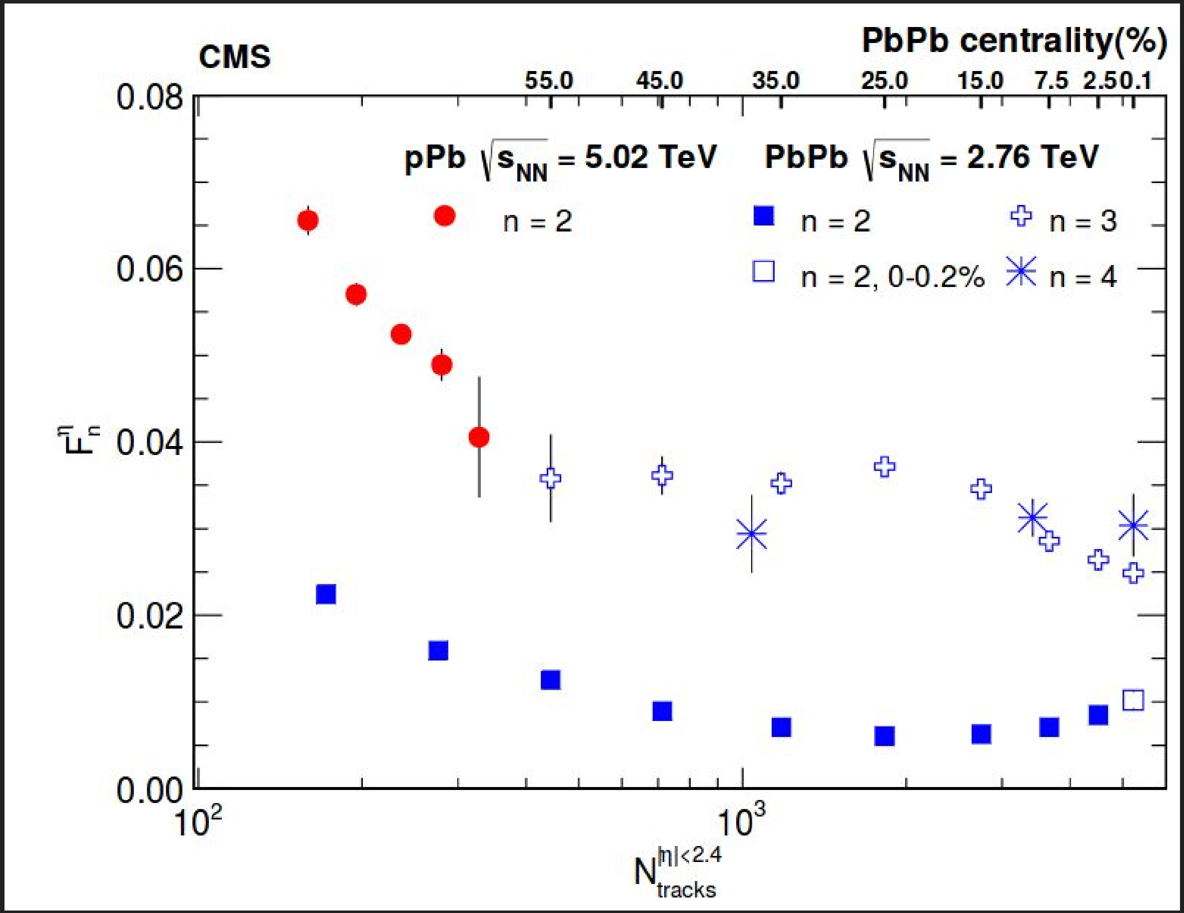
- Significantly larger rotation for n=4 (compared to n=2)
- Nearly independent of choice of reference bin
- Not much centrality dependence

Factorization breakdown in p+Pb:Ψ_2



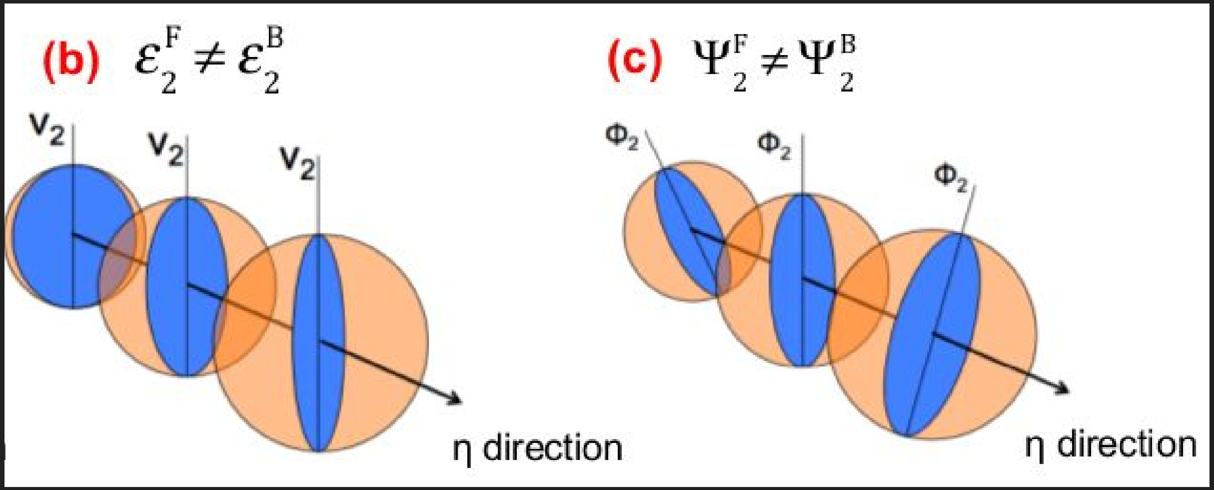
- Significantly larger rotation for p+Pb
- Nearly independent of choice of reference bin

Event-plane de-correlations: summary



- For n=2 first decreases then increases with centrality and harmonic order 'n'
  - Interesting as p_T dependent factorization breakdown is larger for v_2 than for v_3
- No clear centrality dependence for n=4
- Much larger in p+Pb compared to Pb+Pb at same multiplicity

Drawback of the EP decorrelation measurement



$$r_n(\eta^a,\eta^b) = \frac{\left\langle v_n(-\eta^a)v_n(\eta^b)\cos[n(\Psi_n(-\eta^a)-\Psi_n(\eta^b))]\right\rangle}{\left\langle v_n(\eta^a)v_n(\eta^b)\cos[n(\Psi_n(\eta^a)-\Psi_n(\eta^b))]\right\rangle} \sim \left\langle \cos[n(\Psi_n(\eta^a)-\Psi_n(-\eta^a))]\right\rangle$$

- Cannot differentiate between magnitude fluctuation and EP rotation
- Interprets magnitude fluctuation effects as rotation effects

Summary

- Recently there has been much progress in studying longitudinal multiplicity and flow fluctuations (Both theory and experiment)

- Measurements include
    - FB Multiplicity correlations from ATLAS
    - EP rotation measurements from CMS

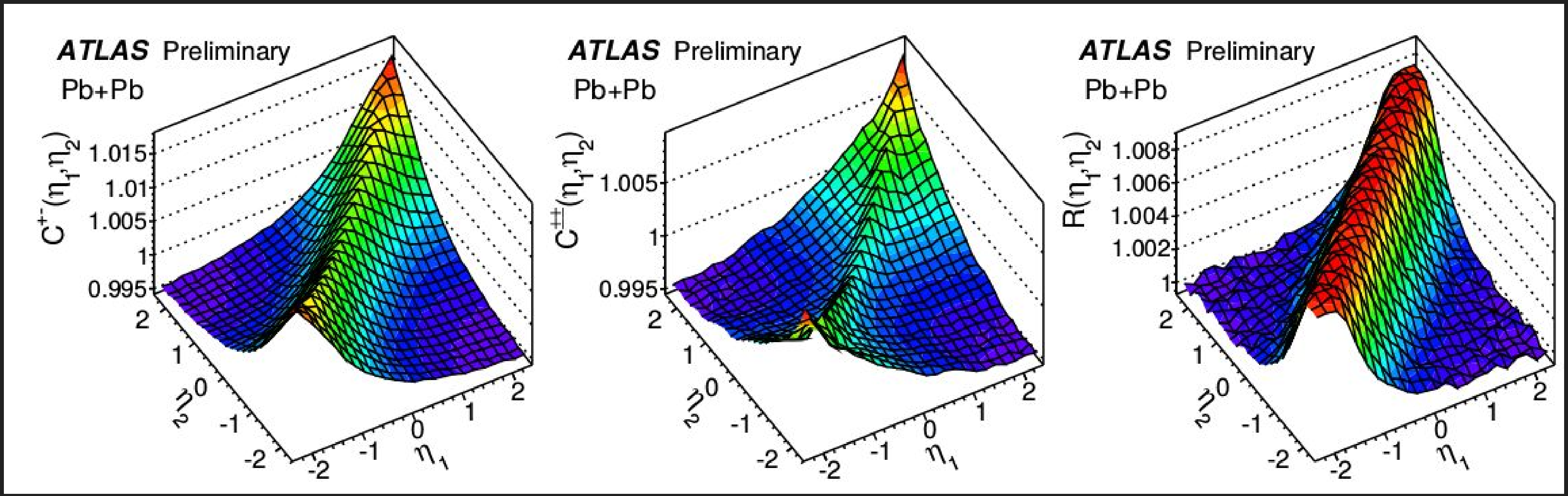
- FB Multiplicity correlations:
    - Linear multiplicity variation is dominant source.
    - Very similar correlations for pp, pA and AA collisions
    - Systems not too dissimilar after all?

- EP rotations
    - Significant rotation is observed increasing with harmonic order ‘n’.
    - Larger for pA than for AA
    - Must develop observable to disentangle magnitude fluctuations from EP rotation

- Will be interesting to make these measurements in Cu+Au, d/He+Au systems at RHIC

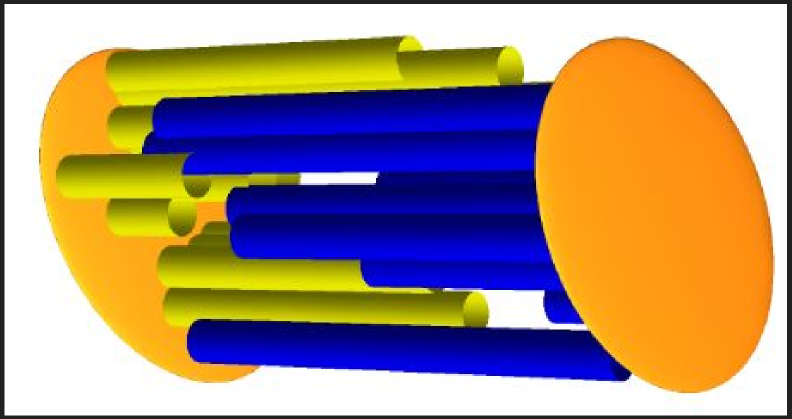
Short-range correlations : Estimation

Opp-Charge pairs Same-Charge pairs Ratio



- Short-range correlations depend strongly on relative sign of particle pairs
- Much larger for opposite-sign (left) than like sign pairs (right)
- Ratio has some interesting properties

Other mechanisms of longitudinal fluctuations



Sources of fluctuating length along η.
arXiv:1512.01945 (W. Broniowski, P. Bozek)